

# Towards artificial muscles

P. G. de Gennes  
 Collège de France, 11 place M. Berthelot  
 75231 Paris Cedex, France  
 e.mail: pierre-gilles.degennes@espci.fr

October 12, 2009

## Abstract

Solid state actuators (piezoelectric, ferroelectric, ...) deform under an external field, and have found many applications. They respond fast, but their mechanical deformations are very small. There is a need for soft actuators, giving larger responses, but necessarily less fast. This paper describes the early attempts by Katchalsky and others, and the problems which showed up -related to time constants, and, most importantly, to fatigue. Two current attempts are reviewed.

*Key words:* actuators, artificial muscles, nematic polymers, electro osmosis.

*PACS numbers:* 64.70 Md, 65.70 +y, 66.30 Qa.

## 1 Introduction

As soon as Kuhn understood the flexibility of polymer chains, and the origin of rubber elasticity, his student A. Katchalsky thought about the possibility of transforming chemical energy into mechanical energy, using gels swollen by water. His first idea is explained on Fig.1. Starting from chains which carry acid groups ( $CO_2H$ ) and adding  $OH^-$  ions, one obtains a charged network ( $CO_2^-$ ) where the chains stretch by electrostatic repulsions. If one then adds  $H^+$ , the system returns to neutral, and the gel contracts.

This system, however, does not allow for many cycles. Adding  $OH^-$  really means adding soda ( $NaOH$ ) and adding  $H^+$  means adding hydrochloric acid ( $HCl$ ). At each cycle, one thus adds one mole of  $NaCl$ , and this ionic solute screens out the electrostatic interactions: the system dies out fast.

Katchalsky solved this problem by an intelligent trick: he used ion exchange ( $Na^+$  against  $Ba^{++}$ ) where  $Ba^{++}$  binds two ( $CO_2^-$ ) groups and contracts the gel.

His group produced active fibers of this type[1]. However, the process did not gave rise to useful applications, for a number of reasons:

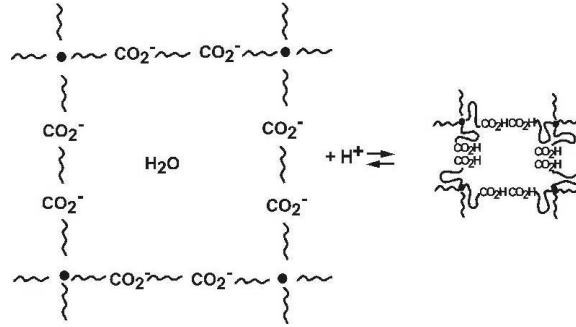


Figure 1: The simplest mechanochemical device: going to acid  $pH$  causes contraction.

1) Time constants: what is implied here is diffusion of ions from a bath to a fiber, and diffusion is always very slow. And even if the ions were injected locally (by highly divided electrodes, or, by conducting polymers) the diffusion of water remains necessary to swell or deswell.

2) Fatigue: if we swell a gel by water, the swelling process starts at the outer surface, and creates huge mechanical tensions in a thin region: buckling instabilities occur[2] and fractures show up. There is little hope for an artificial muscle which breaks locally at each cycle.

In the following section, we present two attempts where these difficulties are taken into account. It may well be that none of them gives a durable answer, but the trends are interesting.

## 2 A semi fast nematic muscle

The starting point here is a nematic network schematized on Fig.2. At low temperatures, the system is elongated. At higher temperatures, above the nematic isotropic transition point  $T_{N1}$ , the network contracts. Networks of this type have been synthesised by a very intelligent technique [3].

Of course, thermal effects have their difficulties: the diffusion of heat is faster than the diffusion of solvents, but is still slow. This led us to think about a *semi-fast* system[4]: here we heat up rapidly the system by a light pulse (having some adsorbing dyes inside) and induce the nematic isotropic transition. The contraction time of rubber in a sling -is related to the velocity of shear waves in the rubber, and is typically of order 1 millisecond. When we want to close the cycle, we have to cool down the sample (by a few degrees) and this takes a long time (seconds). But this semi fast actuator might be of some use.

To avoid fatigue, we conceived a system based on block copolymers (Fig.3) which is hopefully well protected. The fabrication of these sophisticated copolymers requires artistic chemistry, and is under way[5].

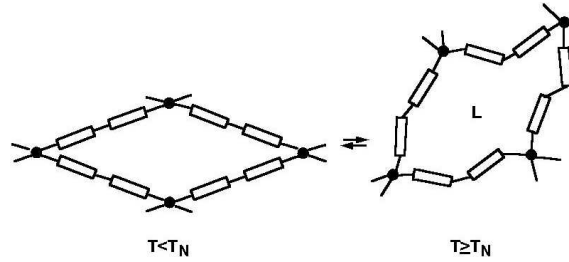


Figure 2: A nematic network: below the ordering point, the network ( $T < T_N$ ) is elongated. Above ( $T \geq T_N$ ) (in the isotropic phase) it contracts.

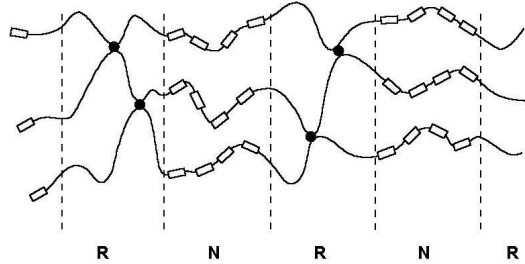


Figure 3: A lamellar phase of block copolymers with rubber portions  $R$  and nematic portions  $N$ . The  $N$  portions are temperature sensitive as in fig. 2

### 3 Nafions

A completely different approach has been used by M. Shahinpoor and coworkers [6]. Here, the basic material is commercially available, cheap, and robust. It is a "nafion": a fluoropolymer containing some fixed  $SO_3^-$  groups plus  $Na^+$  counterions and small water pockets which are inter connected (Fig.4). Shahinpoor was able to set up electrodes, with large contact areas, on both sides of a thin nafion sheet, by formation of platinum nanoparticles.

When such a sheet is put under a mild voltage ( $\lesssim 1$  volt) it deforms as shown on Fig5. The basic process appears to be simple. When a  $Na^+$  ion moves, it drags some water with it towards the cathode: thus the cathode swells, while the anode contracts.

There is also an inverse effect: if a bending torque is applied to the sheet, a voltage difference shows up.

The features can be described rather simply (like all electro osmosis effects) in terms of two coupled fluxes (normal to the plate): the electric current  $J$  and the water flux  $Q$ [7]. The corresponding forces are the electric field  $E$  and the

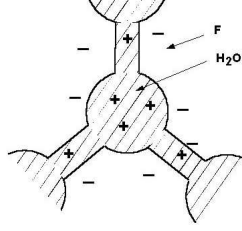


Figure 4: A simplified view of wet nafion membranes. The matrix is a fluorinated hydrocarbon network. At the surface, fixed sulfonated groups bring a negative charge. In the water pockets, the counterions (+) are mobile.

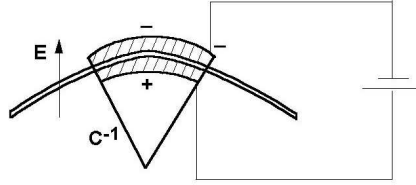


Figure 5: A typical mechanoelectric experiment with a wet nafion membrane

pressure gradient  $\nabla p$  :

$$J = \nabla E - L_{12} \nabla p \quad (1)$$

$$Q = L_{21} E - K \nabla p \quad (2)$$

Here,  $\sigma$  is the conductivity,  $K$  the Darcy permeability and  $L_{12} = L_{21} = L$  is a coupling coefficient.

1) The direct effect corresponds to  $Q = 0$  and  $\nabla p = L/KE$ . The pressure gradient induces a curvature  $C$ : in the absence of any external torque, they are related by:

$$\nabla p = kYC \quad (3)$$

where  $Y$  is the Young modulus, and  $k$  is a numerical factor involving the Poisson ratio  $\sigma_p$ :

$$k^{-1} = (1 + \sigma_p)(1 - 2\sigma_p) \quad (4)$$

2) For the inverse effect, we have  $J = 0$ , and  $E = L_{12}\nabla p$  is proportional to the curvature.

One can construct order of magnitude estimates for the various coefficients. For the very small pores of interest here, the standard (Smoluchowski) description of electro osmosis is not very adequate. The following is an alternate view point:

a) The conductance is:

$$\sigma = \frac{ne^2}{\zeta} \quad (5)$$

where  $n$  is the number of sodium ions per unit volume and  $\zeta$  a friction coefficient:

b) The Darcy permeability  $K$  is of order:

$$K \sim \phi \frac{d^2}{\eta} \quad (6)$$

where  $\phi$  is the water volume fraction,  $d$  the size of the water pores, and  $\eta$  the viscosity.

c) Finally, the coupling coefficient  $L$  can be estimated from a situation where  $\nabla p = 0$ , assuming that each  $Na^+$  ion drags a volume  $w$  of water. Then:

$$Q = LE = vw \quad (7)$$

where  $v = eE/\xi$  is the drift velocity of the ions. It seems that, in this way, we can arrive at a reasonable picture of the whole effect.

We are currently studying the time response, ie the frequency dependence of all these processes. But some general features emerge:

- 1) The system is robust, and can be cycled many times.
- 2) The frequency response is typically in the range of 30 cycles -ie slow, but still of possible interest for some biomedical applications.

On the whole, it is clear that soft actuators are still in their infancy; but it is also clear that they will soon become important.

## References

- [1] A. Katchalsky, M. Zurik, J. Polymer Sci., 16, p. 221-234 (1955)

- [2] T. Tanaka, S. RT. Sun, Y. Hirokawa, S. Katayama, J. Kucera, Y. Hirose, T. Amiya, *Nature* 325, p. 796-798 (1987).
- [3] H. Finkelman, H. Köck, G. Rehage, *Makromol. Chem. Rapid Comm.*, 2, p. 317 (1981).
- [4] P. G. de Gennes, *C. R. Acad. Sci. (Paris)*, 324 II, p. 343-348 (1997).
- [5] auroyP. Auroy, P. Keller, private communication.
- [6] M. Shahinpoor, Y. Bar-Cohen, J. O. Simpson, J. Smith, *Smart Mat. Struct.*, 7, p. R15-30 (1998).
- [7] P. G. de Gennes, M. Shahinpoor, K. J. Kim, to be published.